FINAL REPORT

Nonlinear Circuits and Neural Networks: Chip Implementation and Applications of the TeraOPS CNN Dynamic Array Supercomputer

Grant No. N00014-98-1-0052

December 1, 1997-November 30, 2000

L. O. Chua

Principal Investigator

Nonlinear Electronics Laboratory

University of California, Berkeley

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20010309 029

We have successfully implemented and completed all research tasks described in our original proposal, and have made several important breakthroughs during the grant period Dec.1, 1997-Nov.30, 2000. In this final report, we will focus on the following major advances in research and CNN chip implementations.

(i) We have developed the architectural and electronic layout design, and characterization of the first-ever analogue RAM (ARAM) chip for our CNN Chip Set Architecture. We have also tested the chip and found it to be fully operational.

(ii) We have invented and developed the *local activity principle*, which has become a fundamental tool for designing Cellular Nonlinear Networks with complex and emergent behaviors;

(iii) We have invented several new cell configurations and powerful new templates based on mathematical morphology;

(iv) We have developed analogic CNN subroutine designs for several practical applications, including coding, optical flow estimation, bubble – debris classification, etc..

Throughout the 3-year grant period, we have collaborated closely with Professor T. Roska in Budapest, Hungary and with Professor A. Redriguez-Vazquez in Seville, Spain in connection with the ONR CNN NICOP grants.

Task 1: *Making the ARAM in the CNN Chip Set Architecture*

An analog random-access memory chip (ARAM) in a 32x256 configuration has been designed and fabricated via MOSIS using Hewlett-Packard's 0.5-micron CMOS technology. The main parameters of our successfully tested ARAM chip are as follows:

- 637 analog memory cells/mm^2,
- 7-8 bits of accuracy,
- 10 MS/sec input rate and 1MS/sec output rate,
- 80-100 msec storage time.

Our innovative circuit design solutions was responsible for its robust operations. A series of electrical tests at our laboratory in Berkeley had validated our design goals. In addition, our functional tests have confirmed that the specified accuracy (7 bits I/O with monotonicity) is enough to produce practically distortionless images when viewed by a human observer.

Task 2: *Exploiting the local activity principle*

Complex systems made of a very large number of nonlinear dynamical systems distributed in space and interacting locally often exhibit emergent, self-organizing, and sometimes exotic properties in space and time. Although these phenomena have been widely studied and described, no solid and rigourous conditions have been established for explaining the genesis of these systems and why they exhibit such surprising strange phenomena.

The local activity principle has been applied successfully to several important CNN cell types. Conditions in the CNN parameter space have been determined under which complex phenomena, at the edge of chaos, could occur. These results have become the foundation for our future research on emergent computation and self organization.

Task 3: *Design and qualitative analysis of new cell configurations and templates.*

The design of more powerful analogic CNN Universal Machine chips requires the development of new and robust templates and subroutines.

Mathematical-morphology based tools are very attractive for the algorithm designer and have provided a powerful tool for solving many difficult video and image processing problems. Their implementation via classical computers, however, is inefficient. We have demonstrated that the CNN computing technology is the natural platform for implementing mathematical morphology.

We have designed several new cell configurations. The so called piecewise-linear universal cell is a construct which is efficient in many situations, especially for implementing local

Boolean operators. In addition, optimal subroutines for non-separable Boolean operators have also been developed.

In the field of qualitative dynamic behaviours, some new conditions on non-symmetric A-template for ensuring complete stability have been found. Our studies on using CNN dynamics for solving the shortest path problem have been very successful and explicit conditions for chaos transitions in CNN have been derived.

Task 4. *Analogic CNN subroutine*

In the framework of application case studies, several practical CNN subroutines have been developed. One important breakthrough that we have made is in the area of optical flow calculations. Highly efficient analogic CNN algorithms for coding moving images have been designed.

Condition-based maintenance for detecting the start of deterioration in helicopter engines is an ambitious task for today's technology. Teaming up with Dr. Abe Schultz at the Naval Research Laboratory, we have developed analogic CNN algorithms to solve both the basic image preprocessing and also the subsequent classification task to detect debrie particles in high-speed oil flows inside a helicopter gear-box. A major difficulty in solving this problem is the presence of a large number of air bubbles in the flow. An efficient wave metric has been successfully developed and implemented on CNN-UM Chips to solve this problem,.

Several preprocessing algorithms have also been developed sucessfully *for image fusion*.

References

In the attached documents, all publications supported from ONR grant N00014-98-1-0052 are listed with short abstracts. A reprint of each paper is also included in this final report.

List of publications with abstracts

Chua, L.O..
``CNN: A vision of complexity,"
International Journal of Bifurcation and Chaos, vol.7, no.12, pp. 2219-2426, Oct. 1997.
Published also in a book form : World Scientific, 1998
Abstract
After a comprehensive overview on the CNN paradigm as well as the CNN Universal Machine, the revolutionary principle of local activity, as a root of complexity, is introduced. Constructive methods in testing the local activity principle in CNN cells are described.

Cruz, J.M.; Chua, L.O.
"A 16*16 cellular neural network universal chip: the first complete single-chip dynamic computer array with distributed memory and with gray-scale input-output"
Analog Integrated Circuits and Signal Processing, March 1998, vol.15, (no.3): 227-37.
Abstract
This paper present a 16x16 Cellular Neural Network Universal Chip with analog input and output ports, which can read in and process gray-scale images in the analog domain. The chip contains about 5,000 analog multipliers and has been fabricated in a 0.8μm CMOS process.

Zarándy, Á.; Stoffels, A.; Roska, T.; Chua, L.O.
"Implementation of binary and gray-scale mathematical morphology on the CNN universal machine"
IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, Feb. 1998, vol.45, (no.2): 163-8.
Abstract
A cellular neural network (CNN)- based morphological engine is proposed. An effective implementation method of binary and gray-scale erosion, dilation, and reconstruction is introduced. The binary morphological operators are successfully implemented on an actual CNN universal chip. Experimental results are shown.

Gilli, M.; Civalleri, P.P.; Roska, T.; Chua, L.O.
"Analysis of time-varying cellular neural networks for quadratic global optimization"
International Journal of Circuit Theory and Applications, March-April 1998, vol.26, (no.2): 109-26.
Abstract
The algorithm for quadratic global optimization performed by a cellular neural network (CNN) with a slowly varying slope of the output characteristic is analyzed. It is shown that the only CNN which finds the global minimum of a quadratic function for any values of the input parameters is the network composed by only two cells. If the dimension is higher than two, even the CNN described by the simplest one-dimensional space-invariant template $\hat{A}=[A_1, A_0, A_1]$, fails to find the global minimum in a subset of the parameter space. Extensive simulations show that the CNN described by the above three-element template works correctly within several parameter ranges; however, if the parameters are chosen according to a random algorithm, the error rate increases with the number of cells.

Dogaru, R.; Crounse, K.R.; Chua, L.O.
"An extended class of synaptic operators with application for efficient VLSI implementation of cellular neural networks"

IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, July 1998, vol.45, (no.7): 745-53.

Abstract
A synaptic operator based on multiplication requires a large amount of hardware, particularly in digital implementations. In this brief, we introduce an extended class of synaptic operators which includes the standard multiplication as a particular case. The properties of the extended class of operators are established. Among these, it was found that the global stability theorem of cellular neural networks (CNN's) is applicable to the extended class of synaptic operator as well as for the multiplier-based synapse. The effectiveness of this new operator is demonstrated by a few examples of examples of discrete-time CNN operating in all possible dynamic modes (equilibrium, periodic and chaotic).

Shi, B.E.; Roska, T.; Chua, L.O.
"Estimating optical flow with cellular neural networks"
International Journal of Circuit Theory and Applications, July-Aug. 1998, vol.26, (no.4): 343-64.

Abstract
The cellular neural network is a locally interconnected neural network capable of high-speed computation when implemented in analog VLSI. This work describes a CNN algorithm for estimating the optical flow from an image sequence. The algorithm is based on the spatio-temporal filtering approach to image motion analysis and is shown to estimate the optical flow more accurately than a comparable approach proposed previously. Two innovative features of the algorithm are the exploitation of a biological model for hyperacuity and the development of a new class of spatio-temporal filter better suited for image motion analysis than the commonly used space-time Gabor filter.

Dogaru, R.; Crounse, K.R.; Chua, L.O.
"Pyramidal cells: a novel class of adaptive coupling cells and their applications for cellular neural networks"
IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, Oct. 1998, vol.45, (no.10): 1077-90.

Abstract
A significant increase in the information processing abilities of CNN's demands powerful information processing at the cell level. In this paper, the defining formula, the main properties, and several applications of a novel coupling cell are presented. Since it is able to implement any Boolean function, its functionality expands on those of digital RAM's by adding new capabilities such as learning and interpolation. While it is able to embed all previously accumulated knowledge regarding useful binary information processing tasks performed by standard CNN's, the pyramidal universal cell provides a broader context for defining other useful processing tasks, including extended gray scale or color image processing as well.

Dogaru, R.; Chua, L.O.
"CNN genes for one-dimensional cellular automata: a multi-nested piecewise-linear approach"
International Journal of Bifurcation and Chaos in Applied Sciences and Engineering, Oct. 1998, vol.8, (no.10): 1987-2001.

Abstract
This paper introduces a novel CNN cell which guarantees the implementation of any local rule on three variables defined by a Boolean truth table. Moreover, since the output of the cell is completely specified by a simple mathematical formula, it is possible to develop a systematic theory for locating those regions in the CNN genes parameter space where complex behaviors

may occur. The output cell formula is a simple piecewise-linear function, and for the case of a one-dimensional CNN the entire set of 256 CNN genes associated with the corresponding local Boolean functions are listed in this paper.

Nemes, L.; Chua, L.O.; Roska, T.
"Implementation of arbitrary Boolean functions on a CNN universal machine"
International Journal of Circuit Theory and Applications, Nov.-Dec. 1998, vol.26, (no.6): 593-610.

Abstract
The demand for implementing arbitrary *N*-variable logic functions on perceptron-like structures arises quite often in practice. It is well known, that only the linearly separable class of Boolean functions can be implemented in a single step on these structures. This class however, constitutes only a small (and with the increasing *N* exponentially decreasing) part of all logic functions. All Boolean functions can be trivially decomposed into at most 2^{N-1} sub-functions by implementing the minterm or maxterm formulation of the function. This approach, however, becomes rather impractical with the increasing number of variables. In this paper an algorithm is proposed for decomposing arbitrary, linearly non-separable Boolean functions into a series of separable functions, which can be then efficiently implemented as a program for the CNN Universal Machine[1-3] assuming the simplest and most robust hardware architecture. The decomposition is achieved by finding the closest linearly separable compact functions. Robustness issues of the implementation are also addressed.

Majorana, S.; Chua, L.O.
"A unified framework for multilayer high order CNN"
International Journal of Circuit Theory and Applications, Nov.-Dec. 1998, vol.26, (no.6): 567-92.

Abstract
We propose a unified notation for representing any CNN topology. The framework presented here is an attempt to provide a common base for the future development of more general CNN structures, such as multilayer and/or high-order CNNs, which have already been of great interest in many disciplines including biology, chemistry, ecology, physics, etc.

Munuzuri, A.P.; Chua, L.O.
"Shortest-path-finder algorithm in a two-dimensional array of nonlinear electronic circuits"
International Journal of Bifurcation and Chaos in Applied Sciences and Engineering, Dec. 1998, vol.8, (no.12): 2493-501.

Abstract
A two-dimensional array of diffusively-coupled nonlinear electronic circuits, Chua's cells, operating in a bistable regime, is used to find the shortest path connecting two points of a given image. Images are previously stored in the system by modulating the diffusion coefficients. Different types of images were considered, from black and white pictures (where 0 means no propagation and 1 propagation), to analog figures (with many intermediate states) and, in all cases, the algorithm used for such calculations succeeded to find the shortest path. The full description of the algorithm is here described and applied to nontrivial cases where the shortest path strongly differs from the straight line.

Dogaru, R.; Chua, L.O.
"Universal CNN cells"
International Journal of Bifurcation and Chaos in Applied Sciences and Engineering, Jan. 1999, vol.9, (no.1): 1-48.

Abstract
This paper reviews our recent research results beginning from the standard uncoupled CNN cell which can realize *only linearly separable* local Boolean functions, to a generalized universal CNN cell capable of realizing *arbitrary* Boolean functions. The key element in this evolutionary process is the replacement of the linear discriminant (offset) function $w(\sigma)=\sigma$ in the "standard" CNN cell in [Chua, 1998] by a *piecewise-linear* function defined in terms of only absolute value functions. As in the case of the standard CNN cells, the *excitation* σ evaluates the correlation between a given input vector **u** formed by the outputs of the neighboring cells, and a template vector **b**, which is interpreted in this paper as an *orientation* vector. Using the theory of canonical piecewise-linear functions [Chua & Kang, 1977], the discriminant function $w(\sigma)=z+z_0\sigma-s\sum_{k=1}^{m}(-1)^k|\sigma-z_k|$ is found to guarantee universality and its parameters can be easily determined.

Carmona-Galan, R.; Rodriguez-Vazquez, A.; Espejo-Meana, S.; Dominguez-Castro, R.; and others.
"An 0.5-μm CMOS analog random access memory chip for TeraOPS speed multimedia video processing"
IEEE Transactions on Multimedia, June 1999, vol.1, (no.2): 121-35.
Abstract
Data compressing, data coding, and communications in object-oriented multimedia applications like telepresence, computer-aided medical diagnosis, or telesurgery require an enormous computing power – in the order of trillions of operations per second (TeraOPS). Compared with conventional digital technology, cellular neural/nonlinear network (CNN)-based computing is capable of realizing these TeraOPS-range image processing tasks is a cost-effective implementation. To exploit the computing power of the CNN Universal Machine (CNN-UM), the CNN chipset architecture has been developed – a mixed-signal hardware platform for CNN-based image processing. One of the nonstandard components of the chipset is the cache memory of the analog array processor, the analog random access memory (ARAM). This paper reports on an ARAM chip that has been designed and fabricated in a 0.5-μm CMOS technology. This chip consists of a fully addressable array of 32 x 256 analog memory registers and has a packing density of 637 analog-memory-cells/mm^2.

Rekeczky, C.; Chua, L.O.
"Computing with front propagation: active contour and skeleton models in continuous-time CNN"
Journal of VLSI Signal Processing Systems for Signal, Image, and Video Technology, Nov.-Dec. 1999, vol.23, (no.2-3): 373-402.
Abstract
In this paper, a linear CNN template class is studied with a symmetric feedback matrix capable of generating trigger-waves, a special type of binary traveling-wave. The qualitative properties of these waves are examined and some simple control strategies are derived based on modifying the bias and feedback terms in a CNN template. It is shown that a properly controlled wave-front can be efficiently used in segmentation, shape and structure detection/recovery tasks. Shape is represented by the contour of an evolving front. An algorithmic framework is discussed that incorporates bias controlled trigger-waves in tracking the active contour of the objects during rigid and non-rigid motion. The object skeleton (structure) is obtained as a composition of stable annihilation lines formed during the collision of trigger wave-front. The shortest path problem in a binary labyrinth is also formulated as a special type of skeletonization task and solved by combined trigger-wave based techniques.

Szatmari, I.; Schultz, A.; Rekeczky, C.; Kozek, T.; and others.
"Morphology and autowave metric on CNN applied to bubble-debris classification"
IEEE Transactions on Neural Networks, Nov. 2000, vol.11, (no.6): 1385-93.

Abstract
In this study, we present the initial results of cellular neural network (CNN)-based autowave metric to high-speed pattern recognition of gray-scale images, the application is to a problem involving separation of metallic wear deris particles from air bubbles. This problem arises in an optical-based system for determination of mechanical wear. This paper focuses on distinguishing debris particles suspended in the oil flow from air bubbles and aims to employ CNN technology to create an online fault monitoring system. For the class of engines of interest bubbles occur much more often than debris particles and the goal is to develop a classification system with an extremely low false alarm rate for missclassififed bubbles. The designed analogic CNN algorithm detects and classifies single ubbles and bubble groups using inary morphology and autowave metric. The debris particles are separated based on autowave distances computed between bubble models and the unknown objects. Initial experiments indicate that the proposed algorithm is robust and noise tolerant and when implemented on a CNN universal chip it provides a solution in real time.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 6, 2001	Final Technical Report December 1, 1997 to November 30, 2000

4. TITLE AND SUBTITLE
Nonlinear Circuits and Neural Networks: Chip Implementation and Applications of the TeraOPS CNN Dynamic Array Supercomputer

5. FUNDING NUMBERS
N00014-98-1-0052

6. AUTHOR(S)
Leon O. Chua

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Berkeley

Berkeley, CA 94720-1774

8. PERFORMING ORGANIZATION REPORT NUMBER
23051-23800-44-X- -NDLOC

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
N / A

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 Words)***

This final report summarizes the major research accomplishment, including several breakthroughs, in our concerted efforts at chip implementation and applications of the proposed TeraOPS CNN dynamic array supercomputer over the 3-year grant period December 1, 1997 - November 30, 2000. In particular, we have successfully tested the first ever, fully operational analogue RAM (ARAM) chip for our proposed CNN Chip Set Architecture. We have invented a highly original and powerful paradigm called the local activity principle, which has found widebread applications in our quest for a universal paradigm for information complexity. We have designed several novel cell configurations and powerful new templates based on mathematical morphology, and have successfully demonstrated their applications to several defense-related tasks, including solving the bubble-debris classification problem in the conditioned maintenance of helicopters, as well as high-speed target detection exceeding 5000 frames per second.

14. SUBJECT TERMS

15. NUMBER OF PAGES
4 pages + 5 pages references

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL